START Thinking and KEEP Thinking

A CEDA Information Paper

ADAPTIVE MANAGEMENT FOR ENVIRONMENTAL ASPECTS OF DREDGING AND RECLAMATION PROJECTS: REACTIVE AND PRO-ACTIVE.

Central Dredging Association

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Central Dredging Association (CEDA)
Radex Innovation Centre
Rotterdamseweg 183c
2629 HD Delft
The Netherlands
T +31 (0)15 268 2575
E ceda@dredging.org

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ADAPTIVE MANAGEMENT FOR ENVIRONMENTAL ASPECTS OF DREDGING AND RECLAMATION PROJECTS: REACTIVE AND PRO-ACTIVE.

1 Introduction

1.1 Rationale

CEDA is committed to promoting concepts for sustainable dredging and waterborne construction works, as is reflected in the joint publication of the handbook Dredging for Sustainable Infrastructure (CEDA-IADC, 2018) by CEDA and the International Association of Dredging Companies (IADC). As part of this ambition, CEDA supports the concept of Adaptive Management within dredging projects.

Adaptive Management (AM) can be seen as a risk reduction method for projects with inherent uncertainty, put into effect by implementing protocols to reduce uncertainty throughout the general project development. With regards to environmental effects in particular, adaptive management offers a series of operational opportunities to deal with uncertainties and growing insights along the way. Thereby, AM has the power to create a win-win situation for all stakeholders by adopting a workable, tailor-made environmental management plan, based on baseline monitoring and pre-project assessments of environmental effects. The risk reduction as a basic principle to optimise environmental windows is also adopted by the PIANC-CEDA joint working group on environmental windows (PIANC WG227, in preparation).

A number of publications, among which is the CEDA information paper on Adaptive Management (AM), published in 2015 (CEDA, 2015), contain a high-level description of the different aspects of AM (in the context of dredging and marine works). The Adaptive Management Cycle, as proposed by Fischenich and Vogt (2012), includes to Plan, Design, Implement, Monitor, Evaluate and Adapt the process (Figure 1).

1. Plan: Defining the desired goals and objectives, evaluating alternative actions and selecting a preferred strategy with recognition of sources of uncertainty;
2. Design: Identifying or designing a flexible management action to address the challenge;
3. Implement: Implementing the selected action according to its design;
4. Monitor: Monitoring the results or outcomes of the management action;
5. Evaluate: Evaluating the system response in relation to specified goals and objectives; and
6. Adapt: Adapting (adjusting upward or downward) the action if necessary to achieve the stated goals and objectives.

Figure 1: The Adaptive Management cycle, as first proposed by Fischenich and Vogt (2012).

The descriptions in these papers do not include details of AM of specific (environmental) parameters yet. In this fast-evolving topic, various information gaps and subjects that require revision have appeared in the past years.

The CEDA Environment Commission (CEC) has therefore decided to establish a Working Group (WG) on Adaptive Management in dredging, marine works, and land reclamation projects. The Working Group has prepared this CEDA information paper on Adaptive Management in relation to potential environmental impacts related to turbidity and other water quality aspects.

1.2 Who should read this paper

This paper aims to raise awareness of the benefits of AM and to highlight current best practice. On these aspects of environmental management, the paper hopes to inform the following groups:

- employers,
- authorities,
- contractors,
- non-governmental organisations, and
- consultants.

The presented manuscript provides an overview of the key aspects of all project phases to support a structured decision process while implementing AM. It collects case studies demonstrating how AM can be applied to guarantee and/or facilitate environmental compliance, as well as ensuring project completion without significant impact on the aquatic environment. Recent advances in AM such as ‘pro-active’ AM are highlighted and, as such, an update of the Figure 1 is proposed.

It must be clarified that there is no binding standard for AM. The decision as to whether and to what extent AM is to be applied must be differentiated for each project and each dredging management plan.

1.3 Types of Adaptive Management

In practice, different types of AM for dredging projects and sediment management exist. In the past, reactive AM and proactive AM have been described in literature (CEDA, 2015; PIANC, 2010). In this paper, a third type of AM is proposed: Strategic AM. AM can be applied to standalone dredging projects (bound in time and space) as well as long-term processes like the maintenance dredging of a waterway or a port. Definitions of types of AM used in this document are:

1. Classic (Reactive) AM of projects
- During execution of a dredging project.
- Feedback loop based on field monitoring and management actions initiated at the time certain environmental parameters reach alarm indicators or exceed critical compliance thresholds.

2. Pro-active AM of projects (PAM)
- During project planning & execution.
- Ensure compliance with thresholds based both on project design (planning) and forecasting during execution (e. g. using numerical models).
- When predictions indicate alarm levels will be reached, the works planning is adapted.

3. Strategic AM of processes (SAM)
- AM as strategy, e. g. to adapt sediment management to hydromorphological changes in a natural system.
- To obtain flexibility for the management of dredged material.
- To promote understanding of the effectiveness of strategies for handling dredged material.

Pro-Active AM (PAM) can therefore be seen as an extended form of the classical reactive AM, with numerous clear additional benefits. Classical AM entails a feedback loop between works planning, monitoring, and evaluation thereof against environmental objectives (Figure 2). PAM adds a forecasting system to allow for adaptation before actual exceedances of environmental thresholds occur, thus avoiding suspension of works.

Strategic AM (SAM) can be seen as a preparatory phase (often during environmental impact assessment, EIA) in which the system response to certain scenarios is investigated prior to the works. In cases where several dredging projects may occur in the same natural system, SAM offers the opportunity of management at the level of the overall ecosystem, rather than at project level (Figure 3). These SAM studies result in a library of dredging scenarios for which the potential environmental compliance has been demonstrated via simulations. Either these dredging scenarios are applied directly in sediment management (government, port authority) or as input for operational (pro-active) AM for specific projects (e.g., by contractors). If a permit is required for a dredging project under EU-law, any plausible scientific doubts regarding environmental impacts must be clarified beforehand (Water Framework Directive (WFD), Marine Strategy Framework Directive (MSFD, Habitatis Directive (HD), following the precautionary principle). The project can only be performed if all doubts are managed or manageable. A library of scenarios should be in place of which all impacts have been checked through Strategic AM during project planning.

In addition, SAM can be applied during project execution as well, by extending the scenario library during works (vertical text in Figure 2). For example, the environmental effects of proposed modifications with respect to equipment spread or dredging plan can be investigated prior to implementation. Please refer to chapter 6 for more details on SAM.

Application of AM while performing a project is mainly advised in cases where absolute or

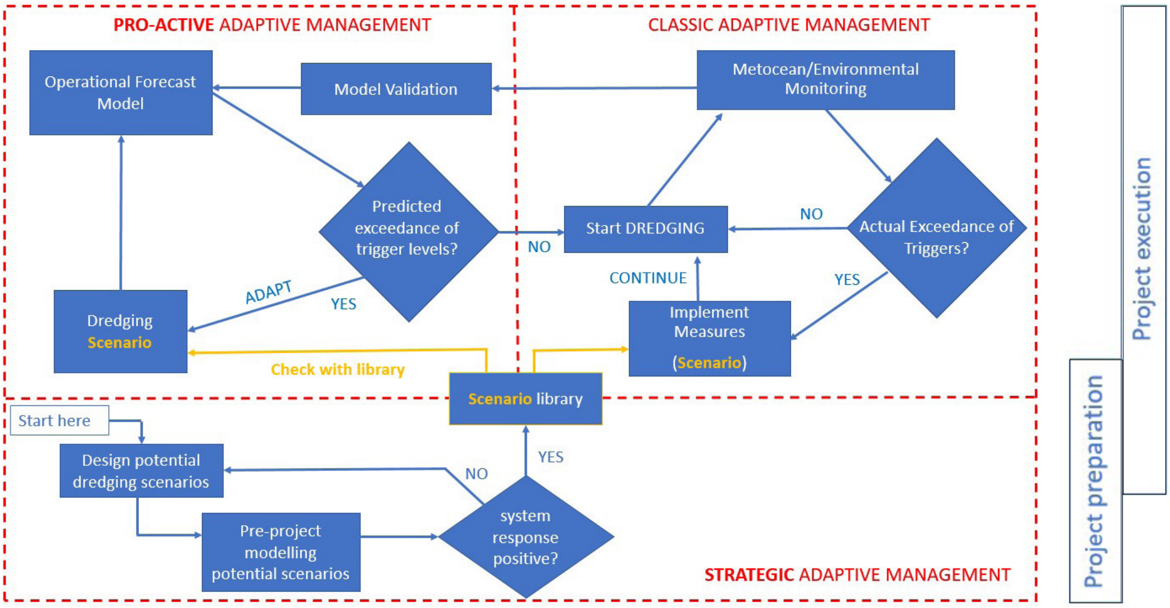

Figure 2: Flow chart for the application of different types of adaptive management. Any combination of classic AM with PAM and/or SAM can be made. SAM can either be over-arching management at the level of a natural system, or the pre-project phase for the (P)AM of a specific project. Therefore, in practise the application of PAM is the combination of boxes ‘Strategic Adaptive Management’ and ‘Pro-active Adaptive Management’.

formal compliance cannot be guaranteed in advance, or where more flexibility is beneficial in the case of overprotective thresholds. Given the complexity of the natural environmental processes, adaptive management should be applied systematically in order to handle the highly interactive ecosystem dynamics. Doing so, the inherent uncertainty is intrinsically covered in the project management. Pro-active AM using forecasting models is advised in case the risk of non-compliance is significant (high damage and/or high probability).

It is important to mention that (P)AM is preferably implemented in a such way that possible work plan adaptations are limited to a predefined set of scenarios described in the environmental monitoring and management plan (EMMP), with only exceptional deviations excluded. This will reassure all stakeholders they can rely on the fact that only project activities without impact or with known impact are cleared for execution.

1.4 Structure of the paper

In chapter 2, the results of a poll investigating awareness of (P)AM in the industry are discussed, and in chapter 3 existing tools and platforms for (P)AM are described. In chapter 4, the best practise according to present insights is provided, and in chapter 5, a more thorough description of PAM is given including the benefits and requirements for the application of PAM. Next, in chapter 6 a new definition for strategic adaptive management is postulated, and notes on the legal framework making (P)AM possible are provided in chapter 7. Finally, possible obstacles for the application of (P)AM, as well as ways to overcome them, are given in chapter 8, and conclusions are written in chapter 9.

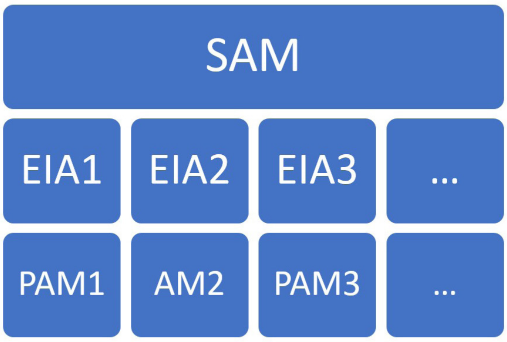

Figure 3: SAM as overarching management at system level; subsequent EIAs and (P)AM applications for specific projects based on the boundaries identified with SAM.

2 Current awareness of AM in the industry

A questionnaire was launched in the sector intended to poll the awareness of AM (reactive or pro-active) amongst different types of stakeholders. A response of 31 valid samples was obtained, which allowed for the outcome to be processed with a certain degree of statistical relevance. The distribution of responses across the different types of stakeholders is shown in Annex 1, Table 3.

Out of 31 samples, 19% indicated to not be aware of the concept of AM, 35% indicated to be aware but without experience, and 45% indicated to have gained experience with AM. Amongst contractors, 25% indicated not to be aware of the concept of AM. Amongst consultants this is 8%, while amongst government and employer categories this is 44% and 0%, respectively. This suggests that raising awareness of the principle of AM within government agencies might be beneficial. When issuing environmental permit conditions, the AM concept can provide more flexibility in elaborating strict compliance criteria.

According to respondents, **adaptation** of timing and dredging equipment is the most effective in reducing the environmental impacts of a project. Adaptation of monitoring strategy

ASPECT	IMPORTANCE
Advanced monitoring technologies to provide better data for modelling and management	88%
Easy to understand presentation of monitoring and modelling outcomes and compliance results to enhance communication with stakeholders	76%
Combining numerical models with measurements	68%
Web-based Decision Support System (DSS) to consolidate monitoring and compliance details and provide a simple management interface	36%

Table 1: Aspects of AM perceived by poll respondents as important for the successful implementation of AM.

and compliance procedures (and thresholds) is seen as less effective.

Important feedback from the industry is information regarding which aspects are the most important to achieve successful application of AM. The response can be summarised in Table 1.

Turbidity is indicated as the operational **parameter most used** by far during AM of marine works, dredging and disposal works in particular. Hydrodynamic parameters, sediment deposition, oceanographic parameters (temperature, chlorophyll, dissolved oxygen, salinity) and contaminants show equal but somewhat lower importance. Biological responses and nutrient levels are least used.

In situ measurements and water/sediment sampling are the **most applied tools** during AM, followed by numerical modelling. Out of a maximum of 5 points, respondents on average gave a score of 3.3 for the use of drones during AM, which is definitely a recent phenomenon. Use of satellite imagery, a technique that has existed for a longer time, received a score of 2.6 on average.

Five different options were provided for **locations** at which environmental parameters are assessed during AM: (1) at project site boundaries, (2) at fixed/variable distance from source, (3) at sensitive receptor sites, (4) in specific zones regarding the attended potential impacts (e.g., high impact, moderate impact, influence) and (5) depending on the specific dredging method and attended potential impacts. All options were given similar scores. Project site boundaries and receptors were given slightly higher scores.

In terms of **limitations** hampering the application of AM, the highest score was given to ‘Flexibility of compliance procedures’, followed by ‘Lack of knowledge’. Time and budget were also scored relatively high, but somewhat lower.

Pro-Active AM (PAM)

Since the present paper also aims to provide information on recent developments and innovations in the practise of AM, the poll included questions on Pro-Active AM (PAM). Throughout all respondents, 55% are aware of the existence of PAM. Of all respondents aware of AM in general, 68% indicate being aware of PAM. This implies that almost one in three respondents already aware of AMhave not yet encountered information about the potential benefits of PAM. It is therefore justified to focus on PAM further in this paper and provide additional information.

Most respondents with experience with PAM confirm that PAM can contribute to:

- Avoiding unnecessary delays or work stoppages due to overly conservative monitoring triggers.
- Reducing the risk of non-compliance due to unforeseen impacts.
- Improving stakeholder engagement.
- Achieving additional environmental benefits.

About 50% of respondents with awareness of PAM have experienced that PAM can reduce execution time by optimising construction methods within environmental limits.

In terms of **limitations** hampering the application of Pro-active AM, the highest score was given to 'Flexibility of compliance procedures', which is the same main limitation given for AM in general. 'Lack of knowledge' and 'Lack of forecast data' were also scored relatively high, which means that information on how to obtain these aspects would be useful in the industry. For this reason, the present paper will highlight the aspect of forecasting for PAM.

See Chapter 5 for more details on a description, the benefits, requirements, and operational phases of PAM.

3 Existing tools & platforms to implement AM

Application of AM or PAM involves numerous data streams to be assessed. In this chapter, an overview of the different tools providing data streams is provided.

3.1 Measurement techniques

Numerous parameters can be selected for monitoring during the pre-dredging and dredging phases to assess the environmental potential impacts related to dredge-induced sediment plumes (i.e. increments of turbidity and deposition rate both in space and time).

The various measurement techniques for monitoring the effect of plume dynamics fall into three general categories:

- Placement of instruments to directly measure parameters in the water column or at the operational equipment (physical or quality parameters).
- Collection of water samples for either field or laboratory analysis.
- Remote sensing.

Monitoring using submerged instruments can occur on two space and time scales: long-term moorings and short-term mobile measurements.

3.1.1 Moorings and tele-transmission

In order to obtain continuous data at a fixed location, monitoring instruments can be attached to buoys or bottom frames. Possible parameters to monitor from such a mooring include turbidity, salinity, temperature, currents, dissolved oxygen, chlorophyll-a. The advantage of moorings is a continuous dataset, allowing for better statistical analysis of the data. Long-term series of data collected before the commencement of the work as input for baseline studies are recommended for most projects.

There are two options to access the data: physical connection with the instruments to extract data from loggers, or tele-transmission. In the first option, no specific instrumentation for tele-transmission is needed, but trips to the mooring buoy are needed on a regular basis to collect the data. This type of data collection is less suited for AM in many cases since the data can often only be interpreted weeks after the observations. Therefore, in many cases, tele-transmission is recommended in order to feed the AM platform with real-time, online data streams. This reduces the number of visits to the mooring to the frequency required for maintenance and cleaning (e.g., biofouling, battery replacement).

3.1.2 Mobile measurements and water sampling

Fixed stations (single point or profiler) allow continuous, long-term monitoring over time for the defining of local background conditions before the execution of the works. The resolution in time is high, but the resolution in space is low due to a limited number of buoys or frames.

Mobile measurements allow monitoring over short periods of time, with high resolution in space, to track the near-field plume. Sampling time can be modulated depending both on operational and environmental conditions (e.g. spill concentrations, water depth, currents) as well as on the purpose of the monitoring project phases (e.g. verification of established thresholds and criteria, model calibration, or verification of the conformity of a numerical result).

The combination of fixed and mobile stations during the execution phase can make the monitoring strategy more efficient, ensuring mobile coverage of those areas not covered by the fixed monitoring system (VBKO, 2003; HR Wallingford, 2003).

The platform used for deploying instruments to collect measurements of in situ hydrographic (e.g., conductivity, temperature, depth, salinity, density), hydrodynamic (water level, waves, current), and other environmental parameters (turbidity, total suspended sediment, dissolved oxygen, nutrients, fluorescence) is mainly dependent on the project specific requirements for the monitoring programme.

Water sampling is performed for different reasons. For one, suspended sediment concentration samples are required to calibrate the optical or acoustic turbidity monitoring instruments. In addition, several properties of seabed sediments and suspended sediments are required as inputs for numerical modelling. Examples of dedicated sediment analysis are sediment grain size distribution and settling velocity. Both properties of natural sediments in the system and sediments in the sources of sediment plumes should be gathered. The latter can be performed with techniques such as an airlift to obtain water samples from the overflow of a TSHD (Breugem et al., 2009).

Usually, mobile measurements require processing before the data can be added to an AM platform. Once the data sets are added, they provide insights to the environmental manager on the behaviour of sediment plumes, as observed in the past. These insights can lead to better-informed decisions on imminent works planning and reduced risk of breaches of environmental thresholds.

3.1.3 Satellite imagery

Satellite imagery can be collected to obtain information on various parameters such as turbidity, chlorophyll-a, mangrove coverage, coastline evolution, and more.

Satellite images have a number of advantages:

- Large areas can be observed at once on a regular basis.
- Historical images dating back long before the start of the works can be obtained for reference baseline analysis and timeline reconstruction of project sites (to observe and measure specific developments in the project area).
- During works, the sources of turbidity can be detected, be that within a defined project or non-project related.
- Images of, for example, turbidity plumes can serve as numerical modelling validation data.

A disadvantage of satellite imagery is the limited depth resolution within the water column. As suspended matter is only observed in the upper layers of the water column, plumes near the bottom might be underestimated. Absolute suspended sediment concentrations are not directly recorded: again, dedicated water sampling is needed to calibrate the observed satellite transparency of the local water. Also, satellite images are not useful in the event of cloudiness. For regions of the world which are prone to cloudy weather types in certain seasons, this can be a significant drawback. However, in that case drones might be a workaround (see next section).

In the past decade, the spatial resolution of satellite imagery has increased dramatically from pixel sizes of hundreds of meters (e.g., MODIS) to tens of meters (e.g., Sentinel 2). This evolution has extended possible applications from large-scale phenomena only, to individual plumes and turbidity in more narrow estuaries and channels. An example is shown in Figure 4, in which sediment plumes due to several activities are seen. The reflectance in the imagery data was corrected for atmospheric deformations and transformed to surface values of Total Suspended Matter (TSM).

The images require atmospheric corrections and conversion from reflectance in different bands to specific water quality parameters. These manipulations need to be performed by specialised experts before upload to the AM platform.

3.1.4 Drones

Drones are used in water quality monitoring on two different levels:

- Submerged (so-called Autonomous Underwater Vehicles, or AUV)
- Above water (so-called Unmanned Aerial Vehicles, or UAV)

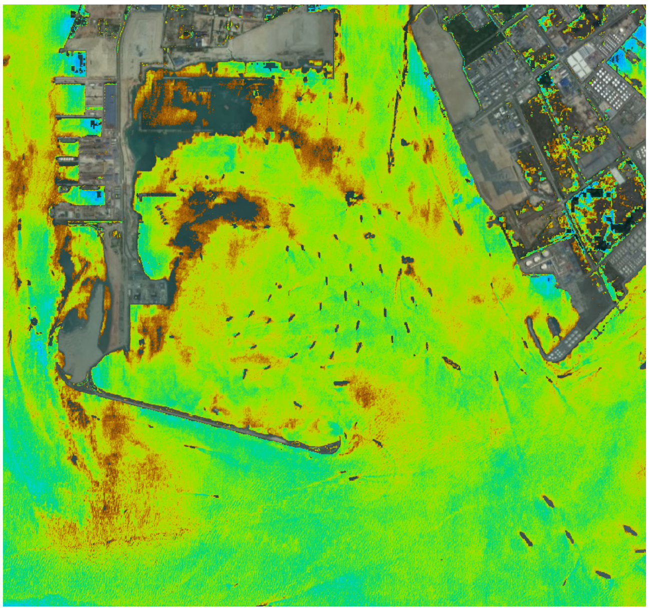

Figure 4: Example of the application of satellite imagery to turbidity management during dredging & reclamation projects. Sentinel 2 reflectance image converted to Total Suspended Matter, making use of a relationship calibrated based on water samples. Green colour denotes low sediment concentration, whereas yellow-brown corresponds to higher concentrations. Narrow dark patches are anchored vessels.

AUV

Underwater vehicles can be programmed to perform a specific task. This task can consist, for example, of completing a pre-programmed route during which observations are taken of different parameters. The use of AUVs comes with specific conditions with respect to flow velocity, safety, and navigation. AUVs have certain benefits in cases where complex spatial patterns need to be mapped on a regular basis. When frequent sailing of monitoring vessels can be avoided, the AUV can provide cost savings and increased frequency of, for example, detailed plume profiling.

UAV

Flying UAVs are complementary to satellite images. The latter have the following disadvantages: cloud cover, low frequency, low resolution. In cases where any of these disadvantages of satellite imagery need to be overcome, drone flights to map, for example, sediment plumes can be a solution. Drones can fly underneath clouds, have spatial resolution up to centimeter scale, and be deployed multiple times per day, at the most appropriate time. Like satellite imagery, depth resolution using UAVs is limited.

3.1.5 Combined techniques

Application of a combination of the above techniques allows us to avoid gaps and to cover all dimensions in time and space with high resolution. This can be achieved by complementing the high-frequency monitoring data from buoys with high spatial resolution data from (less frequent) mobile monitoring campaigns with sailing survey vessels. This is especially useful in areas with strong spatial variation in conditions. For example, turbidity can show strong horizontal gradients in the vicinity of the mouth of a river, near shallow areas affected by wave action, or in dredging-induced sediment plumes.

In the case of very large sites, for example, long stretches of trenching, it is useful to add remote sensing to increase spatial coverage even further.

3.2 Numerical modelling

Numerical modelling enables project staff to have access to a virtual representation of the natural system in which the marine works are carried out. An overview of numerical modelling applications during dredging and reclamation works can be found in CEDA/IADC (2018). The ongoing increase of CPU power and evolutions to open-source codes have improved the quality of and access to advanced numerical modelling significantly. For example, simulated metocean and wave hindcast time series of 25 years and more have become feasible. Similarly, plume modelling for full, multi-year project duration is now possible, enabling, for example, the study of cumulative effects. The main processes involved in AM that can be simulated with sufficient accuracy at the scale of a natural system are:

- Currents & waves,
- Transport of sand and fine sediments,
- Erosion & deposition,
- Water quality (turbidity and water clarity, TSS levels, oxygen level, nutrients), and
- Primary production & algal blooms.

At present, two types of numerical modelling are applied in environmental management:

- Large-scale modelling describing the full natural system in which the project site is embedded
- Small-scale modelling, dedicated to studying smaller-scale processes

The latter type has been applied more frequently in recent years, not only in environmental management, but also to determine design loads of waves, currents, and vessel passage. Most often, Computational Fluid Dynamics (CFD) codes are deployed for this purpose. In environmental management, for example, the distribution of sediment spill rates can be determined, either by approximate empirical relationships (Becker et al., 2015), or by numerical models (Decrop, 2015; De wit, 2015; Saremi, 2014). In Figure 6, an example is shown of a CFD model predicting the horizontal and

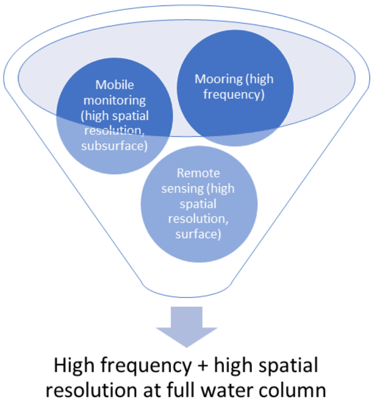

Figure 5: Combining monitoring techniques with high temporal resolution as well as high horizontal and vertical spatial resolution.

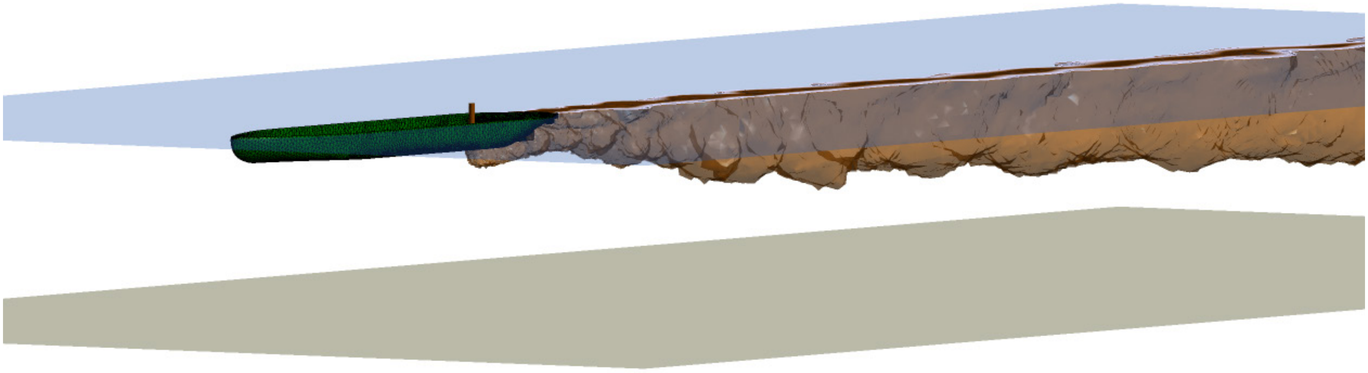

Figure 6: Example of a CFD model applied to determine horizontal and vertical distribution of fine sediments in a TSHD overflow plume (Decrop, 2015).

vertical distribution of fine sediments in a TSHD overflow plume.

3.2.1 Benefits of numerical models

Increases of suspended sediment concentration (SSC) and deposition rates away from the re-suspension source are mainly used to evaluate the extent of the area affected by plume dispersion both in space and time, where the maximum allowed SSC is usually expressed in relation to given thresholds and EQOs (Environmental Quality Objective).

Apart from operational forecasting, numerical models can also be applied prior to the start of the works, to optimise the works for environmental impacts and to simulate what-if scenarios. In the context of AM, these what-if scenarios can predict what will happen if a certain adaptive management (mitigation) measure is executed. Roughly, these what-if scenarios can be divided in four categories, to simulate the influence of:

1. Change of execution method, for example, reduce overflowing, apply different type of equipment, etc.
2. After a long presence in one zone, temporarily switching to a different zone, to allow recovery of the current work zone.
3. Modifying the phasing of operations, for example, working in different zones depending on tidal current direction or depending on wind direction.
4. Implementing direct mitigation measures such as silt screens, bubble curtains, etc.

The set of model outputs (e.g., time series, fields of plume extent) can be integrated into the AM platform when starting the works. In case thresholds are – or will be – exceeded, the model outputs can serve as a library of the effects of different possible AM measures, in order to implement the best adaptation decision on the spot.

Limitations in monitoring techniques and the inherent shortcomings of numerical models are overcome by coupling the two so that measured field data (usually in a point, along a line, or surface area images) is used to calibrate and validate numerical results, while the observed in situ data can be extrapolated in space and time through state-of-the-art process-based three- or two-dimensional models.

3.2.2 Model set up and calibration

The application of numerical models as an aid to decision making and environmental impact assessment should be executed with great care. Different phases of model construction, parameter calibration, and model validation should be completed. Proper model setup and validation can only be reached when appropriate data is available. In many cases, insufficient data is available for model setup (e.g., bathymetry, sediment characteristics, river inflow, etc.) or for model calibration (water level, flow velocity, wave height, etc.). In most cases this is detrimental for model accuracy. A good overview of the different modelling tools currently available to predict the environmental effects of dredging and marine works are given in CEDA/IADC (2018).

Therefore, employers need to establish a monitoring programme within the framework of a modelling–monitoring interaction well in advance of the works, in order to obtain time series with sufficient length by the time EIA or EMMP are prepared. This will not only increase the quality of model calibration and validation but also of derived products such as metocean hindcast modelling, design basis, environmental baseline study, and environmental scenario analysis.

Table 2 provides the reader with a (non-exhaustive) list of datasets required for a plume model setup, calibration, and validation. Point measurements are performed from a buoy or seabed frame, transect measurements are obtained from a sailing survey vessel with instruments such as ADCPs and turbidity sensors. Properties of seabed sediments and

PARAMETER	DURATION	TIME INTERVAL	EXTENT IN SPACE	SPATIAL RESOLUTION	META DATA REQUIRED
Bathymetry			Full system area	1-20m	Vertical reference Coordinate system Date survey
Water level	>1 month	5-30 minutes	Full system	1 gauge per 10-20 km	Vertical reference Coordinates Time zone
Flow velocity (point measurement)	>1 month	5-30 minutes	Site	1 per km	Vertical position Coordinates Time zone
Flow velocity (sailed transects)	1 tidal cycle	10 seconds	0.5-5 km	~10 m (dx) ~1m (dz)	Positioning Time stamps
Turbidity	1-12 months	5-30 minutes	Site	1 per km	Vertical position Coordinates Time zone
River discharges (if any)	>1 year	Hourly, daily	/	/	Units, location, time stamps
Sediment properties	/	/	system	/	Units, coordinates
Plume monitoring transects (project phase)	3-5 loading cycles	~10 seconds	Vicinity dredging activity	~10 m (dx) ~1m (dz)	Positioning, time stamps

Table 2: List of basic hydro-sediment parameters required to set up and validate numerical modelling tools for AM.

suspended sediments can be acquired using standard sampling techniques such as the Van Veen grab and Van Dorn sampler. In cases of sand-dominated systems, the most crucial element is the sediment size distribution. In cases where the system is dominated by cohesive sediments, flocculation is the most important property of the sediment transport to consider. The settling velocity of flocculated sediments is no longer determined by the size of individual sediment particles but by the floc properties. Actual monitoring techniques exist to obtain information such as floc size and settling velocity via in situ camera systems (Smith and Friedrichs, 2011).

3.2.3 Application during project preparation

Prior to the works, a number of scenarios can be simulated in a numerical model showing the effects of certain phases in the work on environmental parameters. The set of model outputs are integrated into a scenario-library within the AM platform when starting the works, primarily consisting of time series and maps of the environmental parameters. In addition, according to project specific requirements, the moving average or median over a certain time window can be visualised.

The modelled scenarios can be extracted from the database during the works when a certain phase of the works is imminent. The database will show – for different options for executing the works in this phase – whether threshold exceedance is expected. In this way, an execution method for that phase of the works can be selected which is known from preparatory simulations to be likely to be compliant (Figure 7).

3.2.4 Application during project execution

During project execution, the models can be used for short-term forecasting of compliance

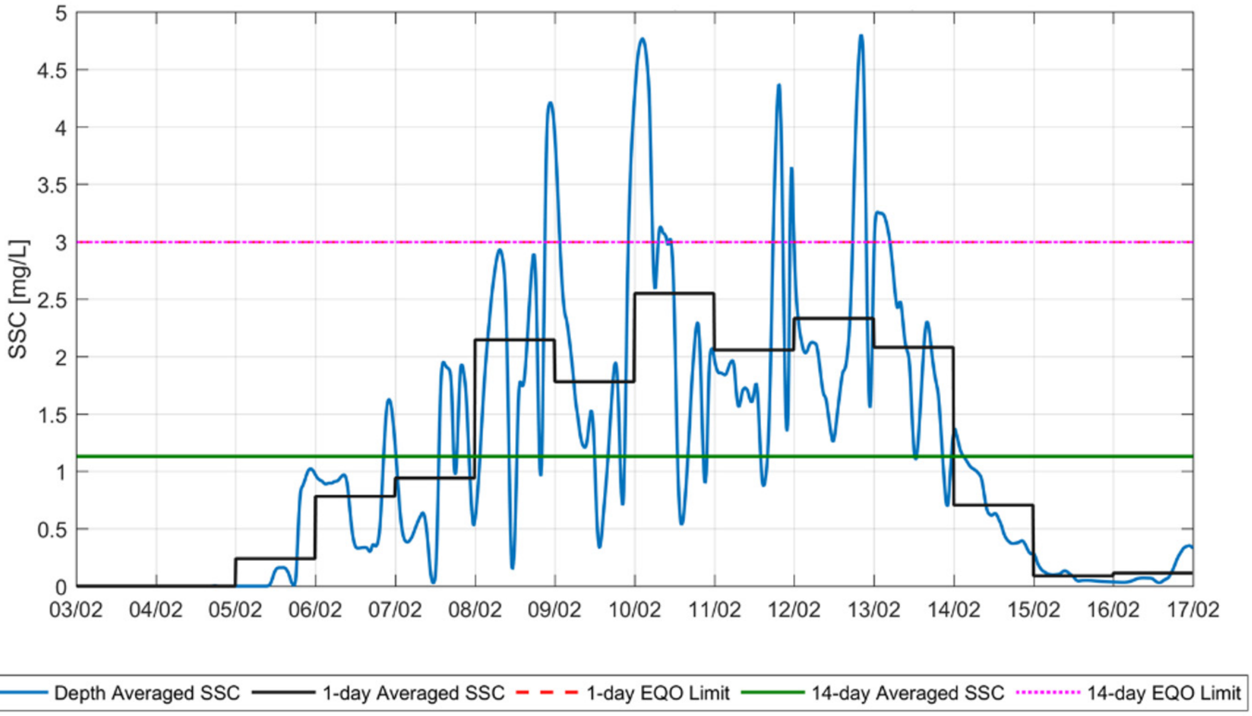

Figure 7: Example of suspended sediment concentration (SSC) in a dredging plume as a result of a scenario simulation (blue line). In this project, different environmental quality objectives (EQO) were defined using limits of 1-day average and 14-day average (pink and red dashed lines, both equal to 3 mg/l). The average modelled SSC values are calculated and shown in the plot indicating compliance (green and black full line).

with environmental EQOs, but also for the same purposes as during project preparation (for example, in the case of study number two in section 9.2). Indeed, during project execution, it might be required to investigate additional scenarios for ongoing and planned work packages, since it is advised to perform ongoing model recalibration and validation based on data becoming available more abundantly during the project. After such a recalibration, it is good practise to repeat a sub-sample of the scenario simulations to check consistency of results with prior model versions.

During project execution, opportunities might be detected to accelerate the project execution by means of increasing production, for example, by using larger dredgers, a higher number of dredgers, or a different type of equipment. In cases such as this, the environmental compliance of such a change can be predicted or optimised using the calibrated numerical models already available.

Further, incident reporting can be aided by numerical models. In case it is suspected that a measured environmental threshold breach was caused by exceptional natural conditions, the relevant period can be reproduced with the numerical models, where possible, supplemented by remote sensing analysis.

3.3 Online platforms and decision support systems

Transparency, agility, and ease of communication are paramount for executing an effective and successful adaptive/proactive environmental monitoring and management plan (EMMP). To achieve this, access to modelling, monitoring, and compliance documentation must be provided as much as possible online and in real time for all relevant stakeholders. To do so, deploying a platform integrating the different data streams is beneficial.

Platforms like this provide a clear overview of the incoming data (as a fundamental basis for a uniform visualisation) and allow for the easy production of indicators such as correlations between parameters, daily means, threshold exceedance, et cetera. Based on this digested data, the operator can use the platform directly both as a communication tool and as a decision support tool, not only to detect the need for adaptation, but also to discuss different operational alternatives and decide on the design and implementation of any adaptive measures swiftly.

At the time of writing this paper, these platforms are usually developed as dynamic websites compatible with standard browsers, allowing access globally by logging in using credentials. Different types of user profiles can be created for different types of stakeholders, each displaying a different selection and presentation of the data depending on the needs of the stakeholder.

4 AM: Best practice

In today's practice, dredging and marine construction projects receive, in most cases, an environmental permit in which firm compliance conditions are specified based on an EIA study. This process leads to the tendency to impose strict and overly conservative environmental limits, in some cases invoking an increase in impact from a holistic perspective, for example, due to longer project duration. Effectively, restrictive and static environmental limits as defined in the EMMP might lead to reductions in production and working windows leading to longer project duration and adverse effects thereof.

This sub-optimal process can be optimised in two ways:

- Increase knowledge through baseline monitoring and extensive sensitivity analysis via modelling, resulting in reduced uncertainty and subsequently avoiding overly conservative environmental limits in the EMMP.
- Allow adaptation of both limits and work plan under certain (pre-defined) conditions based on monitoring results and gaining insights in the project impact during execution. Opportunities might even be detected to relieve or reduce the initial compliance thresholds during the works in case the environmental sensitivity of local sensitive receptors proves less than expected.

4.1 Modelling–monitoring feedback system

To make the concept of AM realisable, various data streams are required. Even though AM and related management actions are applied during project execution, it is important to initiate preparations for the data stream allowing AM and associated tiered decision taking protocols well in advance. A comprehensive overview of the data streams in different phases is given in Lisi et al. (2019). In Figure 8, the Monitoring-Modelling Feedback System (MMFS) is visualised on a timeline throughout the project cycle, before, during, and after execution:

- Before Execution: baseline monitoring, model set up and calibration, EIA preparation, EMMP preparation informed by modelling for spill budgets and monitoring strategy.

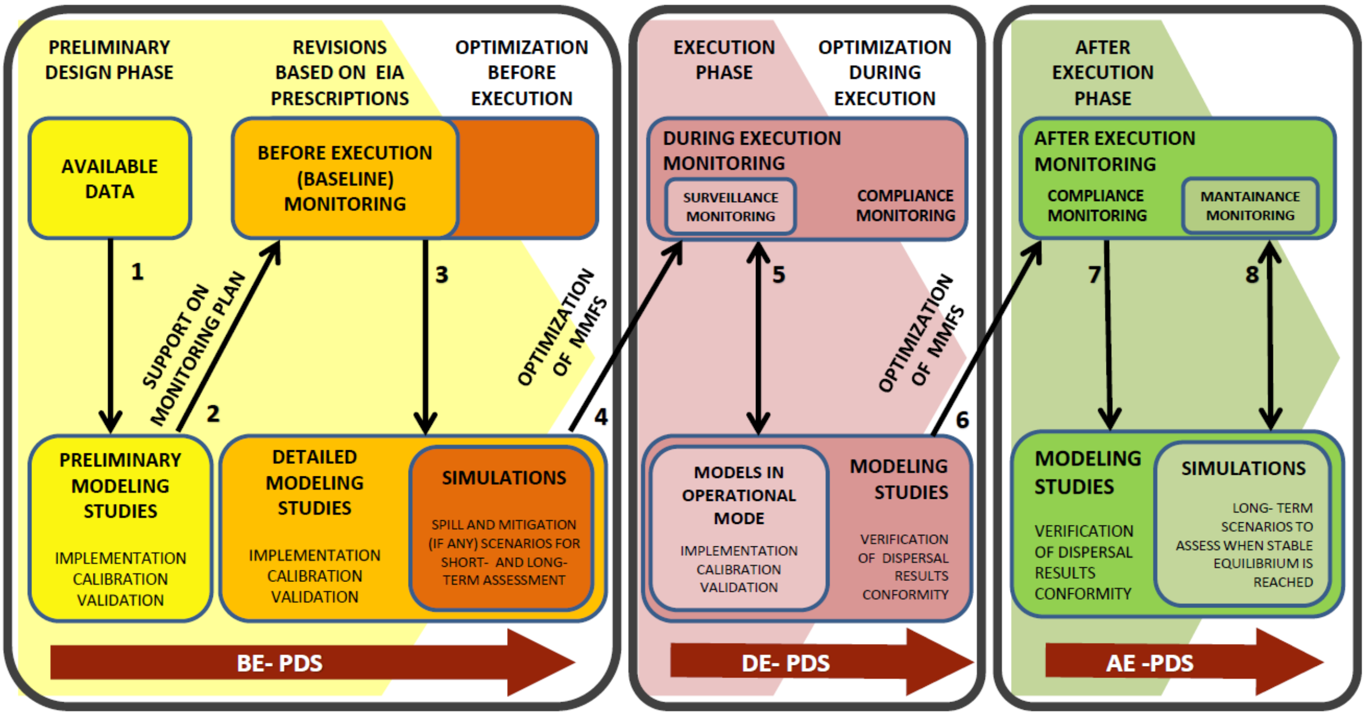

Figure 8: Scheme of the modelling–monitoring feedback system in the different phases of the design, execution, and management of handling operations. In the scheme, MMFS stands for modelling–monitoring feedback system; BE-PDS, DE-PDS and AE-PDS for project data sheets (PDS) before execution (BE), during execution (DE), and after execution (AE), respectively; EIA for environmental impact assessment (Lisi et al., 2019).

- During Execution: monitoring for EMMP compliance, operational modelling to assess work plan adaptations, ongoing model validation.
- After Execution: compliance monitoring, modelling to determine post-project equilibrium.

4.2 Well-defined thresholds and Environmental Quality Objectives

Several forms of sediment plumes can occur during marine works (including dredging, excavation, management of dredged sediments, etc.). The potential impacts on sensitive receptors and water quality justify environmental thresholds and EQOs, to be verified with site-specific monitoring plans (e.g., Anchor Environmental C.A. L.P., 2003; Bridges et al., 2008; Todd et al., 2015; Short et al., 2017; Bray, 2008).

Mitigating environmental impacts is usually managed by limiting the amount of suspended sediments released at the dredging sites or entering sensitive areas. CEDA (2020) outlines a methodology to set turbidity limits to support management actions in case of exceedance, thereby protecting the environment, and allowing for a given dredging operation to commence in an environmentally safe way (in a well-defined operational cause-effect framework as mainly identified and studied in an ESIA).

The basic requirement for defining turbidity thresholds is to gather all information on the local background conditions of physical and biological patterns, on the adaptation of sensitive receptors to the natural variations of background turbidity, and on the planned works (e.g., dredging method, location, volume and physical properties of dredged material, production rates).

A turbidity limit is considered as consisting of two parts:

- a series of trigger levels with increasing environmental criticality: they consist of a series of intermediate levels (named as warning level, action level, impact level) established in order to prevent, at an early stage, the occurrence of threshold values, based on the intensity and the duration of the stressor
- and a threshold level: a value at which the receptors may exhibit increasing impacts; it may be defined specifically at the receptor or, alternatively, as a more general parameter for the area. It is often representative of stress levels for a given receptor at a given site.

It is important in EMMPs to define in detail how trigger levels are defined in terms of temporal (and spatial) statistics, based on resilience of the relevant sensitive receptors. For example, a trigger level should be defined as either:

- An instantaneous value at a certain position at sampling frequency,
- An average of instantaneous values over a time window, or
- A percentile (e.g., 50% or 95%) of instantaneous values over a time window.

For one parameter, several averaging windows may be applied for trigger levels. For example, a higher average turbidity level during a short period, combined with a lower average turbidity level over a longer period.

Trigger levels should be monitored either at the receptor or at a location at which the response at the receptor is known. Thus, they are identifiable by means of four steps:

1. Identification of sensitive receptors (e.g., habitats and species, resources, and marine uses located in the project's area of influence).
2. Understanding of what they are influenced by (i.e. through light reduction, sediment re-deposition, contaminant and nutrient release, and burial phenomena).

3. Identification of their threshold levels (critical stress levels), intended as the level at which an impact can start to occur for a specific sensitive receptor.
4. Definition of ultimately reasonable trigger levels beyond which measures must be taken before the threshold levels are reached.

Further, Environmental Quality Objectives (EQO) are to be defined based on the trigger levels. EQOs specify how many times per unit of time (week, month, project phase) a trigger level is allowed to be exceeded before management actions are activated.

Similar principles apply for other environmental parameters such as oxygen level, water temperature, contaminants, nutrients, sediment deposition, and salinity (the latter in case saline water intrusion into freshwater bodies is considered an adverse effect).

4.3 Types of management actions

Before starting the works applying AM, clear management procedures in case of EQO breach should be discussed and agreed upon with all relevant stakeholders, generating clear and straightforward procedures and protocols to be put in place. The employer needs to be aware of the fact that all of the procedures need to be applicable if necessary.

The trigger levels are the turbidity levels that need to be respected to ensure that the threshold level is not reached and EQOs not breached (CEDA, 2020). It is thus a specified criterion used for the management of dredging operations. When a trigger level is exceeded, the need for a management action will be assessed and, if necessary, implemented to prevent undesired/negative impacts.

A typical approach is to define three different types of trigger levels:

- Warning level: indicating an increase in turbidity levels, providing time to investigate the causes and anticipate/identify possible solutions.
- Action level: indicating that the levels have continued to rise and that mitigation measures need to be taken to prevent the impact level from being reached.
- Impact level: indicating that the increased turbidity levels have the potential to harm the sensitive receptors and that urgent action needs to be taken to reduce them to below impact level or action level.

A monitoring programme, as part of an EMMP, should always be intended as an integral part of the AM system. Indeed, it represents the prime input for driving prompt adjustments to the marine works if needed. When solely monitoring is used, the type of AM used is called ‘reactive’. When forecasts are used in addition to monitoring, a ‘Pro-active’ AM can be achieved (see chapter 5).

Thus, in a pro-active AM approach the decision of changing a work plan should be based on both measurements of the environmental variables and the results of modelled hindcast scenarios for the key variables which have been selected during the assessment procedures.

The feedback from a Monitoring Programme in supporting management procedures generally includes:

- assessment and approval of equipment and work plans prior to the start of operations,
- application of threshold, criteria, and feedback loops with an agreed code of action, and
- adapting planning and environmental approvals of the marine works activities to ensure compliance with the environmental requirements.

For this purpose, the monitoring programme needs a clear definition of the responsibilities of the parties involved. The monitoring programme should include selected parameters that show quantifiable change as a result of impacts from dredging work over a short period of time, since response time is also a crucial part of the management system to be identified.

These variables should be measured either continuously or frequently to allow for a highly responsive AM with short time delays between the start of environmental stress and mitigating measures. Therefore, use of platforms for online and real-time field data transmissions makes it possible to assess at an early stage whether a management action should be taken or not, given the results of the monitoring and future work plans.

Reactive management action

In case trigger levels are reached, an incremental set of management actions may be taken. These actions which are project and location specific (as a function of both contractual compliance requirements and direct ecosystem sensitivity) may include adaptations of:

- Equipment,
- Timing,
- Production,
- Protective shielding methods,
- Methods for dislocating seabed material,
- Vertical displacement technique,
- Horizontal transport techniques,
- Disposal techniques.

Different ways to adapt based on the above aspects are given in literature (BRAY, 1997; BRAY, 2008; CEDA/IADC, 2018). In case management actions are required, a full cost-benefit analysis is advised, taking into account both possible negative side-effects and a full exploration of potential positive environmental opportunities. These can be related to longer project duration due to actions slowing down project progress, thereby increasing the length of the impacts, increasing greenhouse gas emissions, hampering traffic, et cetera. Preferably, this kind of cost-benefit analysis of management actions is prepared in the pre-project assessment, as well as a compilation of a library of management actions 'approved' for the full project or for certain project phases.

Relaxing management actions

It is important to note that management actions can also be used to relax environmental constraints when it is observed that the monitored parameters are not reaching values anywhere near threshold values. In case increasing the intensity of works is beneficial for all stakeholders, without increasing environmental risks, a number of relaxing management actions can be considered:

- Increase production per equipment by reducing limiting factors.
- Increase production per equipment by increasing capacity per unit(s).
- Increase number of pieces of equipment mobilised.
- Reduce number of trips required.
- Reduce cycle time per trip.

4.4 Environmental parameters to assess using AM

A variety of parameters are associated with dredge plume dynamics (sediment dispersion and sedimentation). The selection of parameters to monitor will depend on the purpose of the monitoring effort and conditions at the site. Typical monitoring programmes for dredge-related sediment plumes measure one or more of the following water quality parameters associated with the plume: total suspended solids, turbidity, density, temperature, conductivity or salinity, pH, fluorescence, dissolved oxygen (DO), chlorophyll-a, and deposition height.

Other parameters can be monitored to avoid direct and indirect impacts on receptors related to the induced changes on the marine ecosystem, for example: exporting and burying of microphytobenthos, releasing and retention of nutrients (e.g., phosphorus) from sediments along the water column, and consequences on the distribution of plankton, changing biogeochemical processes along vertical profiles.

To serve as feedback for AM, it is essential that the chosen environmental parameter for monitoring meets some basic demands:

- It must have an unambiguous and easily measurable relationship to the effects of sediment dispersion and sedimentation on the organisms (e.g., seagrass meadows, mussel banks, etc.) which represent the ecosystem concerned.
- The measurement result must be available in a short time (no more than a few hours)
- Background or baseline measurements must be available for the determination of statistically reliable limit values and criteria for judging limits being exceeded.
- The impact of different conditions on the selected variables should be calculable in advance, that is, some kind of conceptual model of the possible cause and effect relationship should be available.

5 Pro-Active Adaptive Management (PAM)

5.1 What is PAM?

In contrast to reactive adaptive management in which actions are undertaken as a reaction to trigger level breaches, pro-active adaptive management applies forecasting to predict an imminent breach and environmental stress.

PAM aims to avoid breaches of trigger levels by adapting the operational working and management schemes in the project preparation phase and based on feedback during the project's execution. The information used in PAM is a combination of relevant background data (e.g., baseline monitoring, metocean conditions, modelling results, and feedback from earlier dredging campaigns), as well as online and real-time data gathered during the works. All these data are typically combined into a previously developed numerical model for the project (e.g., in the ESIA-study), that can be used to simulate the planned dredging scenario as well as alternatives in case the predicted turbidity levels would exceed the trigger levels.

PAM is typically associated with both forecast models as well as with an operational online monitoring programme to validate (hindcast) the planned scenarios. Figure 9 illustrates the adaptive management based on monitoring input, as well as the pro-active management based on model simulations. The model is based on existing environmental conditions (currents, waves, sediment properties, etc.) and manageable processes (e.g., production, use of overflow, spatial spread of dredging equipment, etc.). By altering these processes, the probability of trigger level exceedance can be simulated in order to choose the optimal dredging scenario. The feedback loop in PAM is further illustrated by the graphical schematic in Figure 10.

5.2 Benefits of PAM

Contrary to (reactive) AM, PAM allows for changes to the methodology and planning prior to the commencement of a certain phase of the works. This avoids a non-compliance situation during the works. From there, strict mitigation measures are maximally avoided,

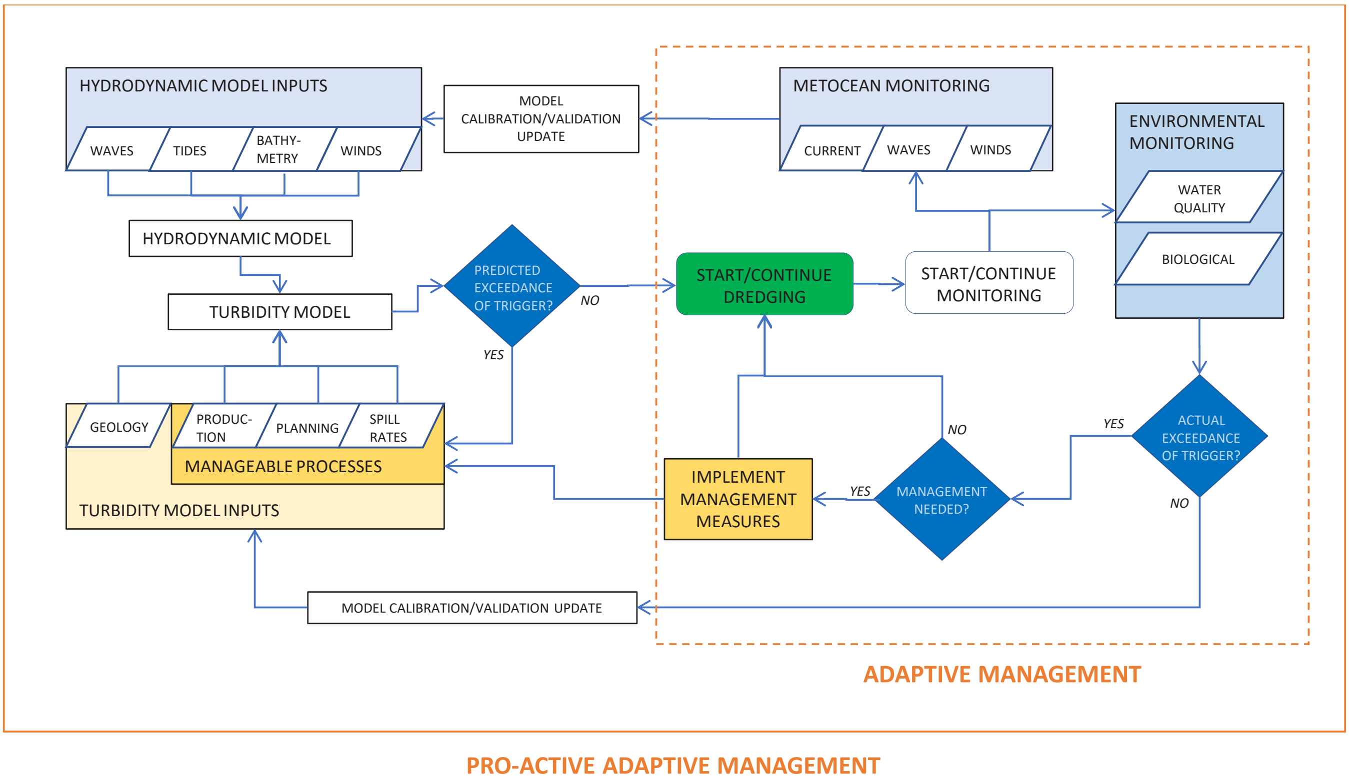

Figure 9: Processes in Classic AM (right hand box) and PAM (combination of both boxes).

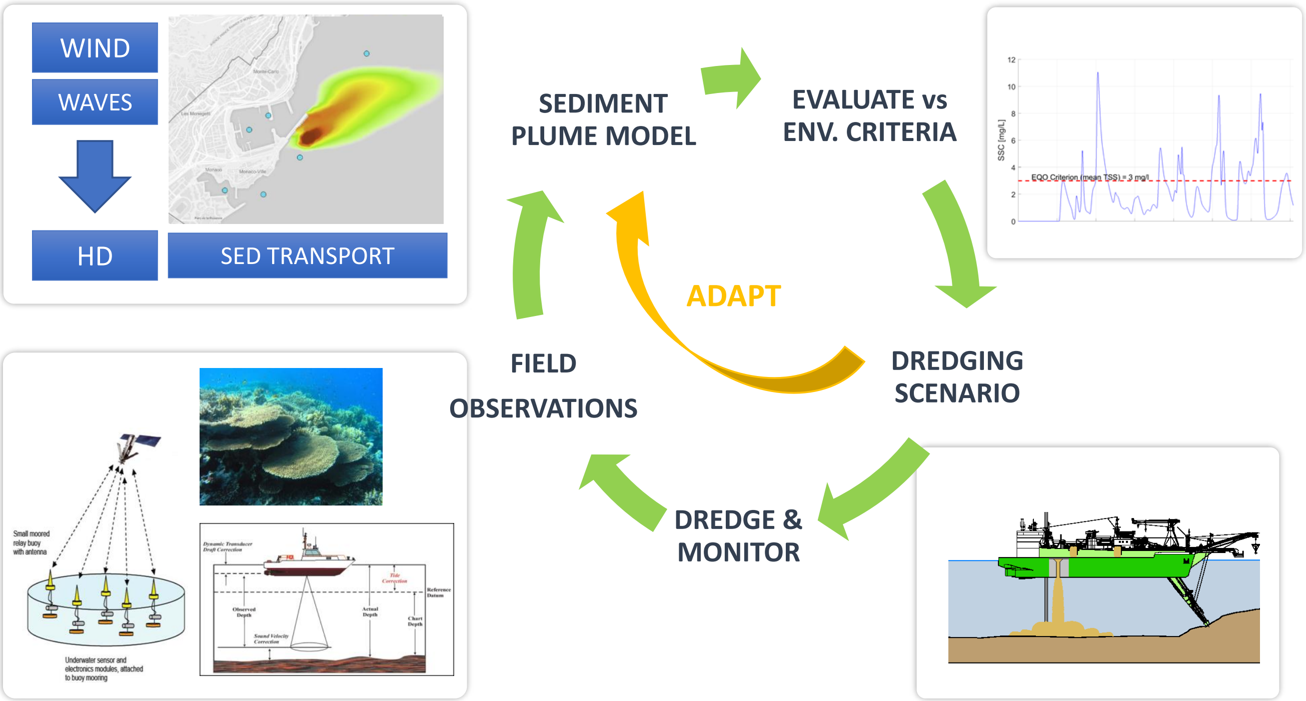

Figure 10: Feedback loop in PAM (IMDC, 2016)

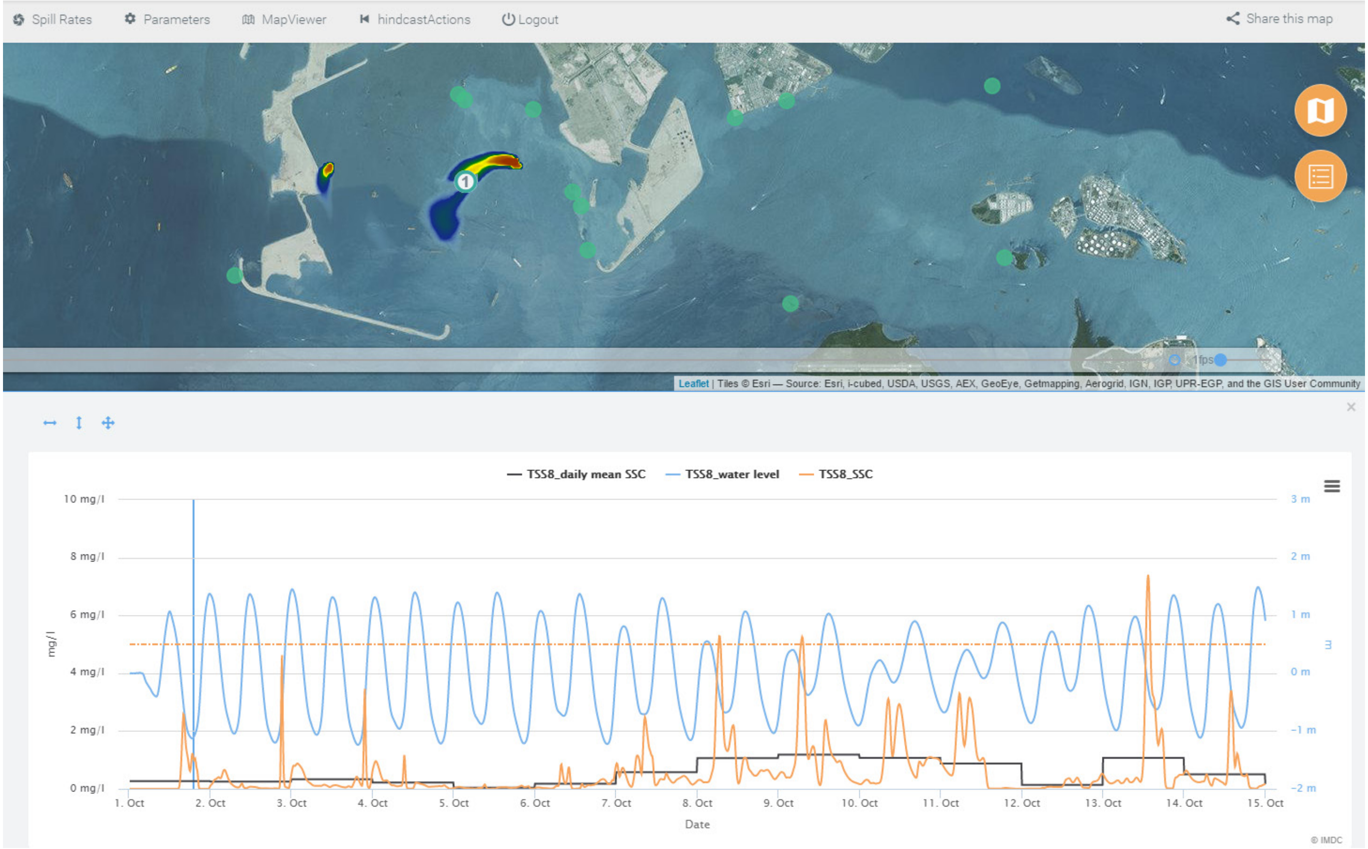

Figure 11: IMDC's Sinapps platform displaying results of sediment plume forecasts and comparison with EQO limits (dashed orange line).

and potential standby costs of equipment are waived. Moreover, it provides a larger variety of possible scenarios and more flexibility in the implementation schedule.

Consequently, PAM can be an economical tool to reduce the risk of shutdowns and reputation degradation. It allows for selection of the optimal scenario for a works activity in the near future, under the condition that forcing data are available to run the forecast models. Generally, the investment required for implementing PAM will largely compensate the costs avoided during execution, for example, due to standby and changes in equipment or methodology. This is especially the case in projects with stringent compliance limits.

The application of PAM will not only provide more confidence to the contractor and employer to be and stay fully compliant throughout project development, but will also create a common sense of security amongst stakeholders regarding project control. Having a common management tool and decision protocol to deal with environmental compliance upfront can help to ease controversy or opposition that might exist against the project.

The quality of the model forecasts is an important aspect of PAM. Technical details on reliability are highly relevant and can be monitored in real time by means of plotting the forecasts of the past few days against the effectively measured parameters. Statistical indication of reliability is a starting point of common decision making. An example for wave height is shown in the screenshot in Figure 12. On the left half of the time series, the ongoing model accuracy is assessed by comparing past predictions with subsequent observations, while on the right half the predicted values, including an uncertainty band, are shown. The uncertainty

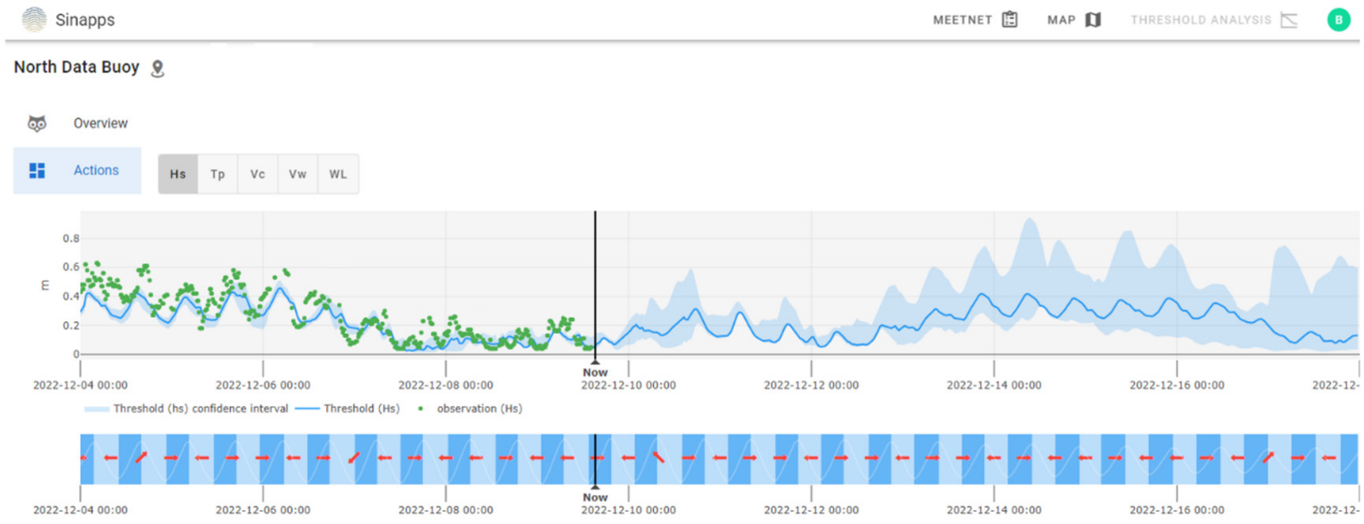

Figure 12: Forecasting system for several environmental parameters, with significant wave height shown in the time series. Predictions including the uncertainty band are displayed for the future, predictions of past periods are compared with observations as a means for continuous model validation (Courtesy of IMDC).

band can be based on so-called ensemble forecasts. This means that the models are run with meteo forecast data stemming from a range of different meteorological models, in parallel. The subsequently obtained 95% uncertainty band is plotted together with the median value. The width of the uncertainty band can be further adjusted based on the effective accuracy of the models in the past few days to take into account the ability of the models to predict conditions during, for example, different wind directions.

5.3 Requirements for PAM

A number of elements are required to operate a fully operational PAM. The basic requirements are real-time monitoring, a graphical interface, and a forecasting tool. Additional elements providing useful information include satellite imagery, drone imagery, AIS data, overlays with project lines, etc.

PAM relies on forecasting tools requiring input data which are not always available, especially when no project activities are taking place yet. However, an increasing number of open datasets are becoming available (e.g., global metocean forecasts), and advanced techniques are now available to provide input data (e.g., remote sensing and tele-transmission).

Knowledge about the expected sediment dynamics to be modelled is required. Numerous studies have been undertaken to understand the sediment transport processes involved during dredging and reclamation projects, for example, spill rates, settling, dispersion, mud/sand interactions (Becker et al., 2015; Smith & Friedrichs, 2011; Decrop, 2015). These studies have aided in the further development of mathematical models and resulted in more accurate simulation outcomes. Further, increasing processor power allows more detailed models to run operationally with acceptable run times and higher spatial resolution.

5.3.1 Real-time monitoring

Fully online and real-time data availability to run pro-active adaptive management is required – this high-quality field monitoring is a basic prerequisite to implement adaptive management.

An EMMP should outline which monitoring techniques are available and operational today to realise an online and real-time field data stream for the parameters relevant to the project, including basic data quality control procedures, data handling and transfer, as well as (statistical) analysis.

5.3.2 Forecasting system

As discussed in chapter 4, according to environmental impact assessment procedures (and other regulatory frameworks) modelling–monitoring interactions are recommended in the Adaptive Management approach for assessing the compliance of selected operational criteria with the established environmental requirements.

- Mathematical models (section 3.2) are generally based on a hydrodynamic module and a sediment transport module. The hydrodynamic module requires data on bathymetry and metocean conditions (tide, currents, waves, and wind). The sediment transport module requires data of sediment characteristics, dredge productions, dredging operations, associated dredging equipment setup, and spill rates (see Figure 8).
- Forecasting relies largely on mathematical models. To get a reliable model output, there is a need for quality input data over a time period and area that are representative for the project scope. Depending on these data, the model can be properly calibrated and validated and as such, provide reliable input to the PAM.
- Monitoring data (see section 3.1) acquired during the project works should be used for hindcast purposes in order to validate the forecasts that were made as part of the PAM. Discrepancies between observations and simulations should be examined to ensure that the selected PAM scenario will still be compliant or needs to be adapted. The real-time field measurements can still be used to perform an online compliance check and associated (induced) turbidity management/mitigation protocol - for example, tiered management approach.

5.3.3 Graphical interaction platform

As mentioned above, a Graphical User Interface or a so-called dashboard is very handy to provide an overview and to visualise all data streams in one platform (section 3.3). From there, a proper communication and visualisation platform becomes available for all relevant stakeholder parties. The basis of such a system is a dynamic mapping tool showing several elements that can be hidden or activated:

- Project area layout: design of structures, progress of works, dykes, cables, environmentally sensitive receptors in project area
- Bathymetric contours
- Locations of monitoring buoys
- Locations at which environmental quality objectives (EQO) are checked

Different tabs or windows are usually planned to organise the multitude of datasets:

- Map viewer
- Time series showing the evolution in time of monitored parameters, including relevant moving averaging windows, daily means or similar
- Time series of simulated parameters using numerical models, including predictions of the past few days (along with observed series for quality check) as well as predictions for upcoming days
- Dynamic map viewer showing time evolution of, for example, sediment plumes in the recent past and near future
- Environmental windows of restriction and/or opportunity showing, for example, green and red bands in a timeline during which works

will be possible in the near future. This can help in designing adapted work plans based on environmental predictions.

5.3.4 Sharing process

A sharing process between the contractor, stakeholders, and the competent authority regarding the modelling–monitoring interaction (to be planned before, during, and after execution of marine works) is also desirable, especially when either large quantities or polluted sediments have to be handled (depending on contractual, compliance or operational requirements). According to IAMDC (2012) the sharing process should include standard decision-making procedures and should be functional to optimize the work plan, the mitigation measures, and appropriate monitoring actions for ensuring environmental compliance (such as modifications of dredging schedules, decrease of spill and overflow using special return pipes, closed grabs or clamshells, silt curtains or screens around dredgers), and the monitoring programme (number, location, and sampling frequency of the stations). As a function of the respective role of each party involved, specific access and rights can be attributed.

5.4 How to operate?

Once the operational PAM-system is in place, it is preferably applied as a decision support tool combined with fixed procedures. Depending on the project's requirements, a routine repeated daily (or other frequency) is established. On day N, this routine includes:

- Collecting data of day N-1 operations (location and production of equipment).
- Restarting plume simulations of day N-2, until end of day N-1, with updated works history production and spills.
- Validating the hindcast model results with the monitoring data.
- Assessing previously started forecasts for possible predicted threshold exceedances. If needed liaise with planning staff to make decisions with respect to works planning for next few days.
- Implementing works planning of the next 5-7 days in the system (location and quantity of spill). Some systems have automated patterns of vessel motions, for example, TSHD sailing up and down a pre-defined track or grab dredgers loading barges which in turn sail to the disposal area.
- Ongoing verification of numerical models via comparison of modelled currents and suspended sediment concentrations with in situ data.
- Uploading of other auxiliary datasets, (e.g., remote sensing, sample analysis, coral health checks, etc.).

The system operator is preferably (but not mandatorily) located at the project site and has several tasks. These tasks include ensuring data input and output run smoothly, collecting operational data from vessel log sheets, defining and starting the model runs according to predefined routines, reporting to an environmental manager. The operator might be assigned tasks with a longer execution time, for example, running scenarios to simulate the impact of significant works planning changes such as modifications in the type and number of active equipment, production changes etc.

The role of the system operator can have different extents. The role might be limited to operations: input and output. In this case, back-office assistance is put in place if required, with a 24/7 support guarantee in case of system failure or numerical model issues. In some cases, the operator is responsible for the latter tasks, but selecting the correct profile with all the required skills can be a challenge.

The need for a (full-time) system operator on site is often seen as a relatively high cost. Therefore, PAM is unfortunately not yet widely applied on projects, unless explicitly required by the employer or the (environmental) authorities. Only a few case studies are available, for example, Saremi et al. (2022) and Chamelete de Vilhena et al. (2015). For most projects, forecast modelling is part of the Environmental and Social Impace Assesment (ESIA), but these models are not verified or updated during the project. However, the implementation of PAM can be very beneficial on projects where stringent water quality limits are applicable in combination with strict environmental windows. In those cases, the Contractor might fail to complete the works within the foreseen window due to delays caused by exceeding a water quality limit. Waiting for the next window will entail large standby or mobilisation costs. Therefore, PAM is not to be seen as an additional burden, but as a fully operational project management tool – assisting both Contractor and Client.

6 Strategical Adaptive Management (SAM)

SAM is mainly used at strategical level for a more global sediment and/or dredging management, but the principle can also be used for other types of environmental management.

The term “Adaptive management” is often used in papers and discussions regarding sediment management in a broader sense:

- for example, as a strategy to adapt sediment management to hydromorphological changes
- to obtain flexibility for the management of dredged material, as a proper base for beneficial (re)use of dredged materials in different applications (e.g., CEDA, 2019)
- to promote understanding of the effectiveness of strategies for handling dredged material

This use of the term AM embeds dredging projects into sediment management on larger scales of space and time (river stretch, river basin, coastal cells, long-term development). It is based on the fact that rivers and coastal waters are aquatic ecosystems with high physical and chemical dynamics. Sediments are in a steady flux, the dynamics vary annually and long term, and they become even more changeable due to climate change. This kind of AM is also based on ecological and economic goals, on the monitoring and modelling of parameters, on thresholds and readjusting management options. It is a realistic approach on how to deal with changing conditions instead of the “might of certainty” (Apitz, 2008).

This kind of adaptive management approach is applicable from dredging projects on local scales up to sediment management plans or strategies on larger scales. There is not a one-size-fits-all solution.

Examples of this kind of adaptive management approach are:

- Flexible implementation of dredging activities depending on environmental conditions like oxygen levels or fish spawning activities,
- Flexible use of different disposal sites depending on boundary conditions like sediment quality or river discharge,
- Flexible use of different disposal sites depending on hydromorphological conditions on the sites,
- Application of beneficial reuse of sediments and in particular dredged materials.

Adaptive management as a strategy for sediment management is particularly important when changing boundary conditions hinder proper long-term planning of maintenance activities. With changing boundary conditions, a continuation of the established maintenance can become economically inefficient, or it can cause avoidable environmental impact. An unmodified continuation of maintenance activities may even become impossible for technical or legal reasons, potentially leading to the successful maintenance of waterways and berths becoming impossible.

However, adaptive management as a strategy does not mean the absence of planning. As a foundation for flexible dredging and disposal operations, a maintenance concept must be developed that includes all options that might become relevant for the adapted operations and is open to future additions or alterations. This maintenance concept should be agreed upon between the relevant stakeholders and it should be incorporated in the tendering process, so that contracts with dredging companies allow for the necessary flexibility.

Next to sediment management, the Strategical AM principle is also applicable to the so-called analysis of alternatives that is part of the EIA process. In this sense, the term SAM is referring to the pre-project assessment of different possible strategies and management actions during execution in the future. As such, a library of possible dredging actions and related environmental performance can be built for and applied to the selection of mitigating measures during project execution.

A case study illustrating the principle of strategic AM is provided in chapter 9.

7 Legal framework

All types of Adaptive Management must provide the fulfilment of legal requirements for hydraulic engineering projects.

- AM during the execution of the project guarantees compliance with thresholds and other project approval obligations if there are doubts regarding adherence to threshold values.
- PAM delivers base information about the environmental effects of the project and how to minimize them, so that the prerequisites for approval procedures can be met.
- SAM helps embed project planning into the long-term development of hydromorphology, water quality and quantity, and sediment dynamics.

The legal framework in relation to environmental knowledge and regulations is expanding more and more, worldwide and especially within the EU. Several EU environmental legislations address the issue of sediment management directly or indirectly: the WFD, the Floods Directive, the Habitats Directive, the Marine Strategy Framework Directive, as well as the Waste Framework Directive.

All types of AM support the achievement of environmentally sound and sustainable project planning and execution. Modelling and monitoring expand our knowledge about the environmental impacts of hydraulic engineering projects.

Legal requirements can relate to the safety and costs of a project or plan or focus on the project's or plan's impact on stakeholders and the environment. A detailed description of the planned activities and their effects is always necessary to meet the relevant legal requirements. When applying PAM, the planning process ends with an optimised project design that is going to be implemented as laid down in the planning and permitting documents. Therefore, applying PAM should not lead to any problems meeting the legal requirements, but rather improve the quality of the plan.

When planning a project that is supposed to be implemented using AM, all possible options that may become relevant in the adaptive process have to be described and their effects on stakeholders and environment must be forecast. If a permit is required for a dredging project under EU law, any scientific doubts on environmental impacts must be clarified before a permit is issued (Water Framework Directive (WFD)[1] , Marine Strategy Framework Directive (MSFD)[2] , Habitats Directive (HD)[3]). The project can only be performed if all doubts are managed or manageable (Guidelines: European Commission 2011, 2012, 2022).

Additional framework conditions for the management of dredged material are the guidelines of international maritime conventions and organisations (LONDON, 2013; OSPAR, 2014; HELCOM, 2015 and 2020; BARCELONA, 1976; BUCHAREST, 1972), the first three with trigger levels as described in chapter 4.2. See also information on the CEDA homepage [https://dredging.org/resources/guidance-documents]. Specific national guidelines fulfilling these requirements complete the framework.

8 Obstacles and how to overcome them

Responses to the questionnaire show that the top limitation to application of AM and PAM is:

- Lack of flexibility in compliance procedures.

This limitation is related to contractual conditions not being tailored to the concept of PAM. In order to make the benefits of PAM possible in a project, flexibility in compliance procedures should be built in in the EMMP. Authorities and employers are thus encouraged to explicitly allow for environmental optimisations via PAM in the permits, tender documents, and preliminary EMMP. Nowadays, forecast models are frequently used as part of the ESIA, but the issued permits are often strictly referring to the conditions and methodology as described in the ESIA. Changes in the construction methods might require a new permit application. PAM can overcome this issue, considering that the PAM procedures are clearly outlined in the ESIA and permit conditions.

Responses to the questionnaire also indicated the following limitations to applying PAM:

- Lack of forecast data
- Lack of knowledge

These limitations are related to access to technical skills. Since in recent times, operational forecasting systems have become more common, and subsequently the skills to set up such systems, the lack of forecast data and knowledge might be a perception of the past.

Remarkably, of all options provided in

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1. https://environment.ec.europa.eu/topics/water/water-framework-directive_en
2. https://environment.ec.europa.eu/topics/marine-and-coastal-environment_en
3. https://environment.ec.europa.eu/topics/nature-and-biodiversity/habitats-directive_en

the questionnaire, the available budget as a limitation is mentioned the least. The decision of whether a PAM system is implemented should be based on a social cost-benefit analysis. The cost to set up a system will be in the same range for most projects. The cost to operate depends on the project duration and the intensity of use (related to environmental constraints). The benefits are to be situated in risk reduction. The risk of shutdowns is reduced, while the flexibility to implement changes in execution method increases. Stakeholder management and filing of claims are expected to become more relaxed in cases where a system is in place significantly reducing the risk of unexpected environmental impact. While budget is sometimes seen as an obstacle for PAM, an analysis of benefits in return can shed a different light.

9 Conclusions and recommendations

This paper offers information to the sector on the benefits of (pro-active) adaptive management, or (P)AM. As a first step, a poll was launched to probe the awareness of different actors in the sector. Based on the questionnaire responses, it was found that awareness of AM is relatively high, but that of PAM is significantly lower. Thus, an increase of information on PAM is deemed necessary for promoting its benefits, for all actors in the dredging sector, but mainly for employers, among which the least awareness was found.

The aim of this paper is to provide a comprehensive overview of the tools and prerequisites required to set up an AM or PAM system. The paper also explains Strategic Adaptive Management (SAM), which, in comparison to AM and PAM, refers to sediment management on larger scales of space and time. More information on the legal framework and how to avoid obstacles for PAM from early project stages is provided, aiming to exclude prohibitive contractual conditions and hence missed opportunities to realise the benefits of PAM.

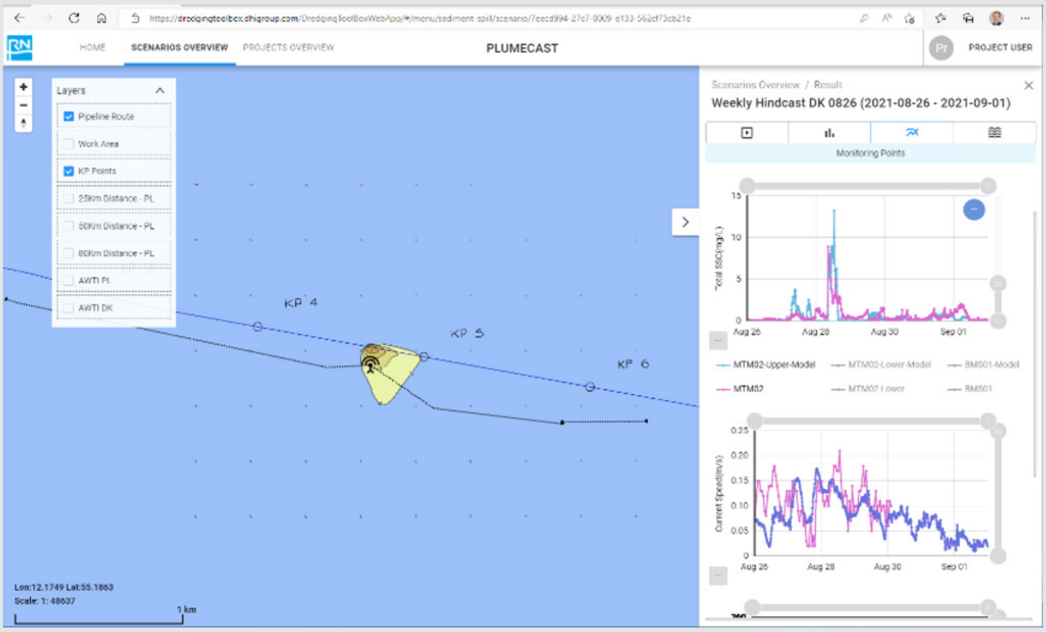
Details on the different elements required for PAM will allow employers and contractors to better assess the timeline and budget required for the preparation of PAM. Combined with the provided insights into its benefits, this allows for decision making on the implementation of PAM via cost-benefit analysis.

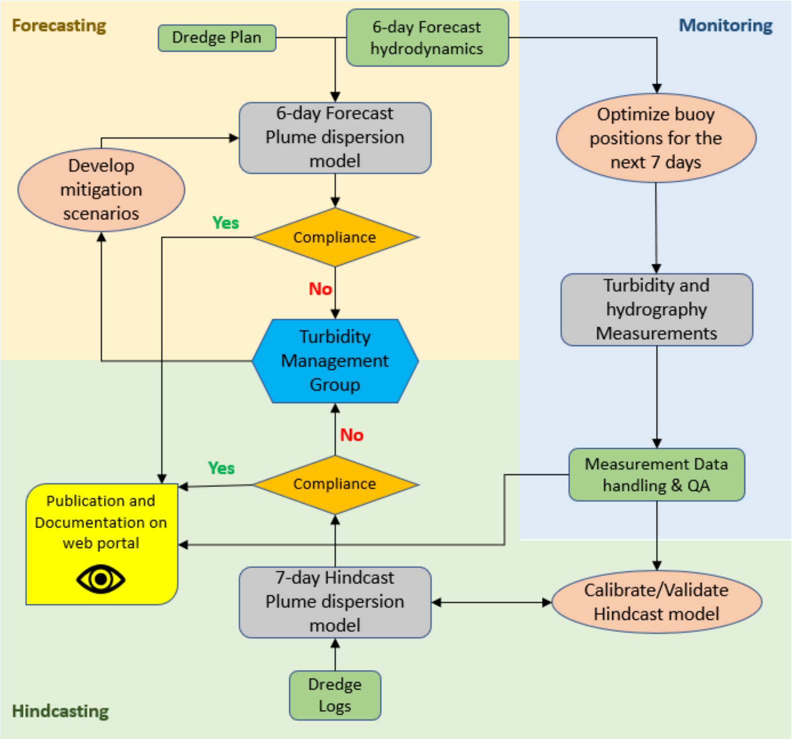
Specific guidelines on how to embed PAM in a project from its earliest stages are not yet available. It is suggested that such documents would be helpful to assist employers and authorities, even though different documents might be needed:

1. for different regions in the world with different types of permitting legislation,
2. and, more generally, for sediment handling projects characterized by different extension (e.g., volumes and duration) and by environmental criticalities (e.g., presence of sensitive habitats and sources of contamination in the intervention area, handling of pollutant sediments).

9 Case Studies

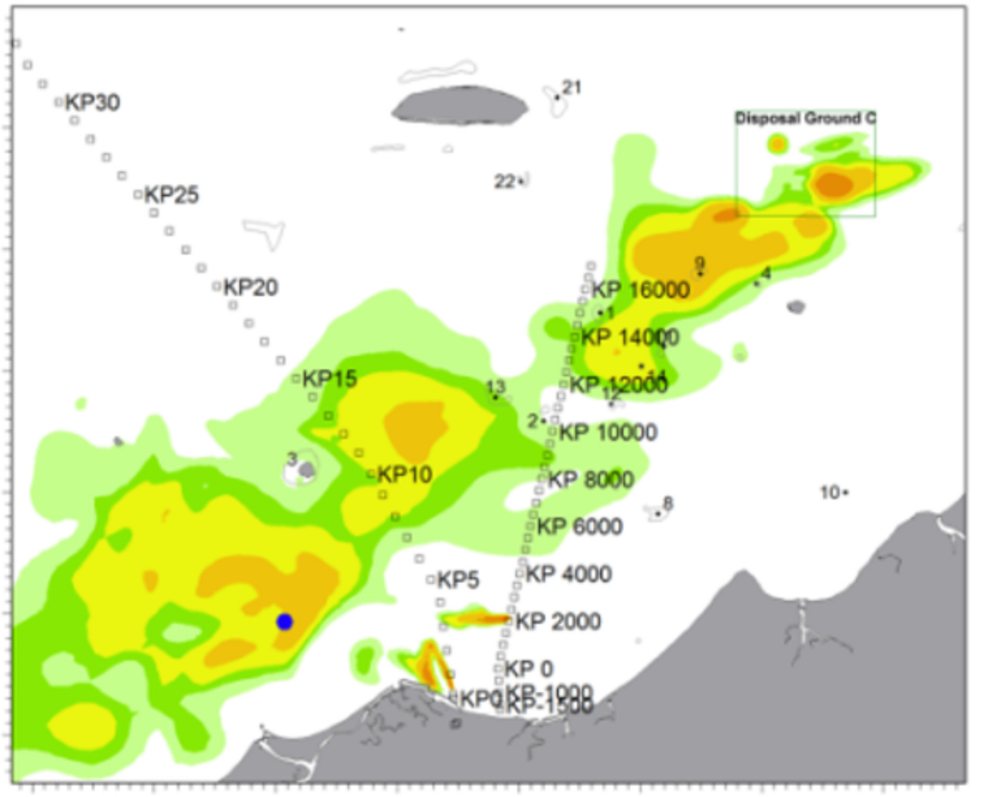
9.1 Application of PAM in pipeline trench dredging and backfilling in Baltic Sea

Project Name	Baltic Pipeline trenching and backfilling
Location	Baltic Sea, between the east coast of Denmark and the northern coast of Poland
Requirement for PAM	In this project the environmental parameter under monitoring and pro-active management was the water turbidity and its variations caused by sediment spill from dredging activities. The monitoring system was composed of online mobile turbidity sensors following the dredgers along the pipeline route, 3D plume dispersion models running on cloud-based servers in both hindcast and forecast mode, and an online platform, “PlumeCast”, which acted as the decision support system by providing access to the combined model and measured data, forecast and mitigation scenarios, compliance analysis, and real-time overview of the positions of the dredgers and monitoring stations. 
Mechanism for adapting dredging activity	As shown in the diagram, the spill management system is comprised of pro-active and adaptive feedback loops within spill modelling and monitoring. The tasks involved in performing the monitoring activities every week are a combination of serialized manual and automatic activities. The following is an example of the tasks taken within the weekly monitoring:

Mechanism for adapting dredging activity (contd.)	• Hindcast:
	  • Setup & execute the weekly hindcast plume dispersion model based on received dredged logs.
	  • Calibration/validation of the weekly hindcast model based on measured turbidity and current speeds.
	  • Evaluation of compliance.
	• Forecast:
	  • Setup and execute the weekly forecast plume dispersion model based on the latest dredge plan.
	  • Evaluation of compliance.
	  • Design & execution of mitigation forecast scenario in case of non-compliance.
	  • On-site monitoring sensors optimization:
	  • Finding the optimized daily buoy location for the coming days, based on the hydrodynamic forecast and latest dredge plan along the pipeline trench.
	

Benefit of application of PAM	Forecast modelling allowed for proactive management of the turbidity levels by 1) predicting the risk of non-compliance, and 2) optimizing onsite monitoring (number and locations of the turbidity sensors). A combination of models and sensor data available through an online platform enabled efficient decision making and communication within all stakeholders.
Further information	Full paper on this case study has been published and presented in WODCON (Saremi et al., 2022). https://www.dredging.org/resources/ceda-publications-online/conference-proceedings/abstract/1140

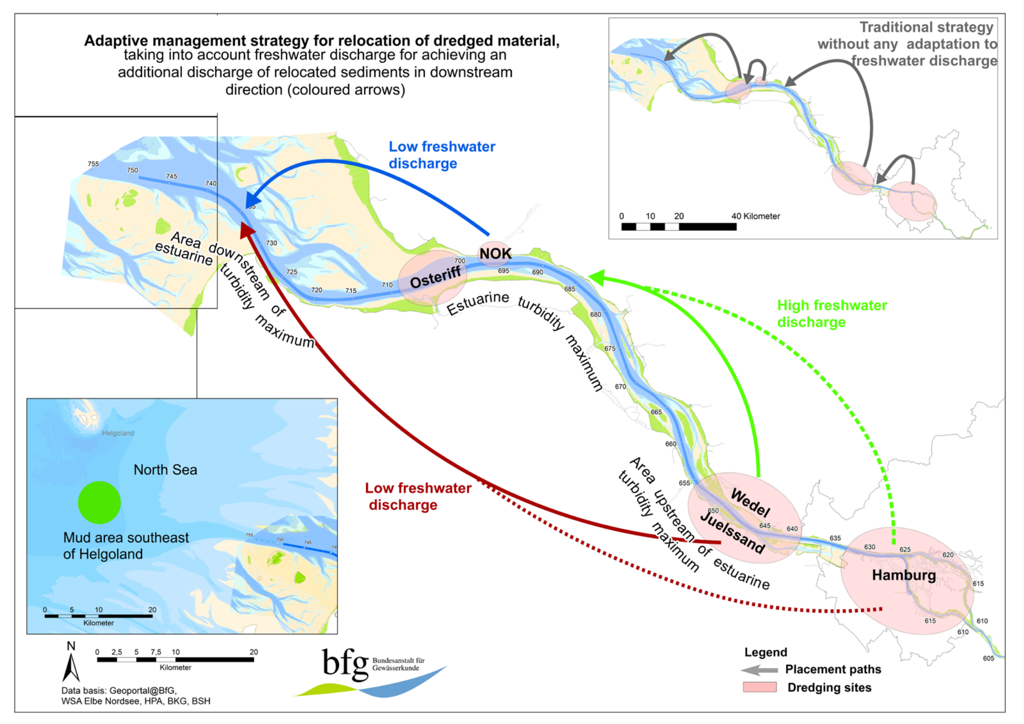
9.2 Application of PAM in the approach to channel dredging in Western Australia

Project Name	Wheatstone LNG downstream
Location	Onslow, Australia
Requirement for PAM	Multiple valuable coral reef sites and sea grass sites surround the dredge area and necessitate strict environmental regulations. The application of PAM entailed prediction of sediment plumes and operational adaptations to avoid breaches of environmental quality objectives.
Mechanism for adapting dredging activity	Extensive monitoring of the sediment concentrations at the coral reef impact sites and around the dredge activities is necessary. Moreover, an operational sediment plume forecasting system is being set up to assess the effects of forecasted dredging works on the impact sites as part of a pro-active adaptive environmental management system. Daily forecast modelling was used as a valuable tool to predict potential future impacts to water quality, including cumulative impacts, enabling proactive management to address issues before they occur. Hindcast modelling (using known source terms) was also a valuable tool to differentiate the relative contribution of various dredging activities when changes to water quality occurred, as well as to differentiate between dredging related and natural effects. 

Benefit of application of PAM	It was possible to monitor and forecast tiered levels to ensure that warnings were available in sufficient time to enable management implementation to avoid reaching the threshold of unacceptable impact that would have stopped the dredging activity. The contractor was able to finish the works without any breaches leading to putting works on hold.
Further information	https://australia.chevron.com/our-businesses/wheatstone-project Boudewijn.decrop@imdc.be Chamelete de Vilhena et al. (2015): Case study: proactive management of dredging operations during construction of the Wheatstone LNG plant facilities, Pilbara Coast, Western Australia. CEDA Dredging Days, 2015.

9.3 Elbe Estuary maintenance dredging

Project Name	Adaptive management strategy for maintenance dredging
Location	Elbe Estuary, Germany
Requirement for AM	The Hamburg Port Authority and the Federal Waterways Authority work with a limited number of sites for the placement of dredged sediment, some of which are located too far upstream to work properly when the Elbe discharge is low. Tidal upstream transport causes sediment recirculation, thus increasing the dredging efforts and causing avoidable costs and environmental effects. In 2014 the annual Elbe discharge dropped considerably below the long-term average and has remained low ever since. The amount of dredging is high, making AM even more necessary.
Mechanism for adapting dredging activity	To address this issue, the Federal Institute of Hydrology (BfG) developed a system analysis that is based on hydronumerical modelling. The study concluded that dredged sediment from the port and upper estuary should be relocated into the zone of the natural turbidity maximum or further downstream in the river mouth, depending on the actual discharge from the upper Elbe. This strategy of AM can be implemented if sufficient viable options for sediment relocation are available.

Mechanism for adapting dredging activity (contd.)	
Benefit of application of AM	HPA and WSV currently pursue the establishment of additional relocation sites in the river mouth and the North Sea. In the next step, a more concrete adaptive management plan can be devised and implemented. This remains a challenge for the coming years, but it is necessary to improve the efficiency of sediment management in Hamburg`s port and the Elbe estuary.
Further information	Systemstudie II (bafg.de) (in German) https://www.bafg.de/DE/3_Beraet/4_Exp_oekologie/WSV_Sedimentmanagementkonzepte_U1/sedimentmanagementkonzepte_node.html 202203204_Gesamtstrategie_Wassertiefen.pdf (hamburg-port-authority.de) (in German, will soon be available in English)

9.4 Maintenance dredging near a storm surge barrier

Project Name	Adaptive management strategy for maintenance dredging
Location	Mouth of the Nieuwe Waterweg ("New Waterway") - Maeslantkering
Requirement for AM	The Maeslantkering is a storm surge barrier within the mouth of the New Waterway (Port of Rotterdam). To be able to close the barrier, the area where the arms move and sink to the bottom must be free of sediment.

Requirement for AM (contd.)

Mechanism for adapting dredging activity

Surveying and dredging for nautical depth are part of the routine operation of the New Waterway. But for 6 months in 2019, a pilot was conducted to reallocate 500,000 m3 sediment 2 km upstream of the barrier instead of sailing out towards the North Sea. This pilot, conducted to lessen the greenhouse emission of dredging by shortening the sailing distance, had the risk of siltation at the barrier. A requirement was a weekly bathymetry survey and a trigger value (+10 cm siltation) for immediate dredging (see Figure 2 and 3).

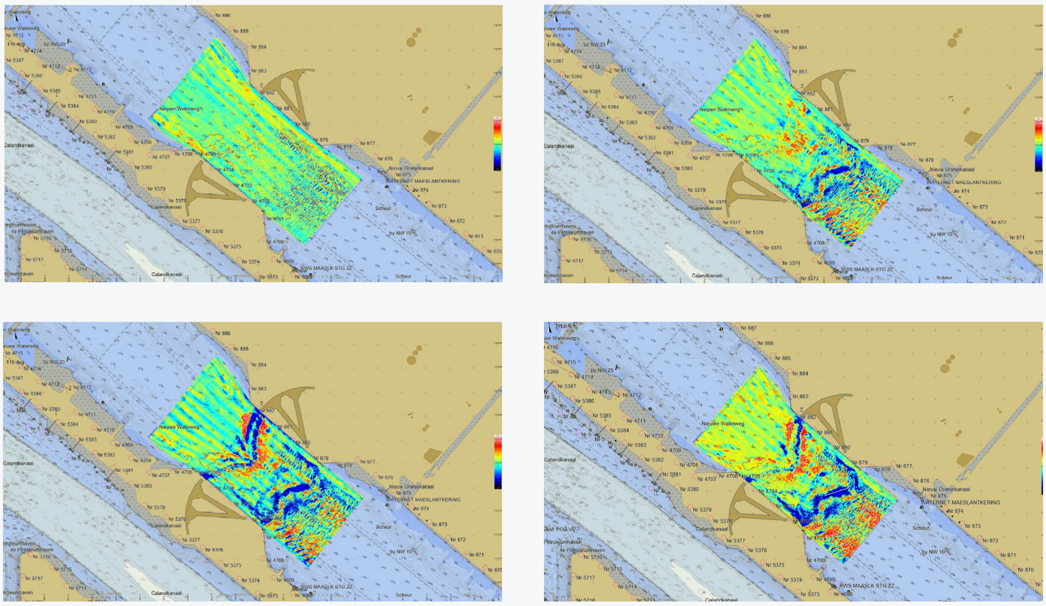
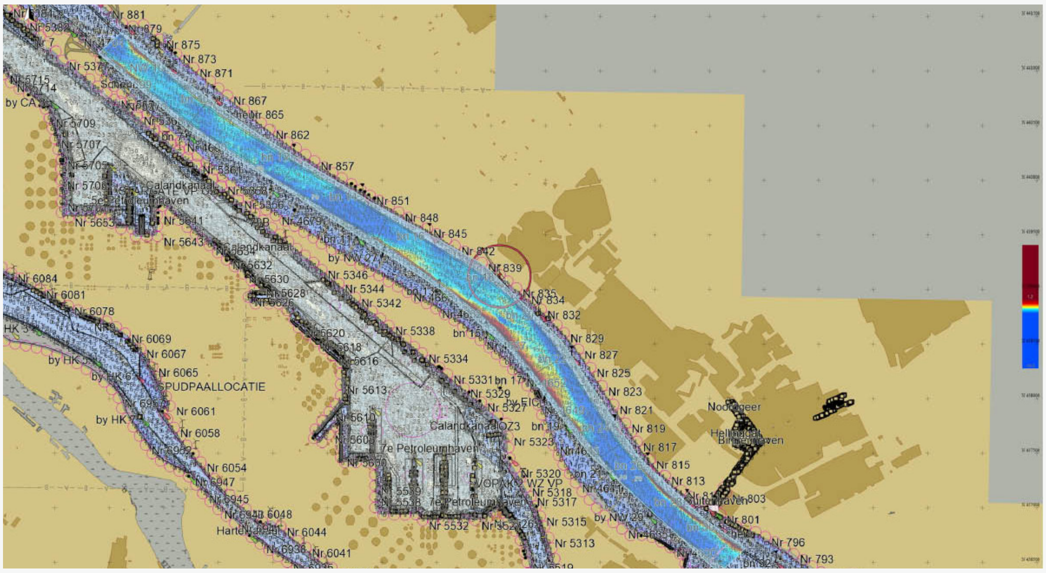
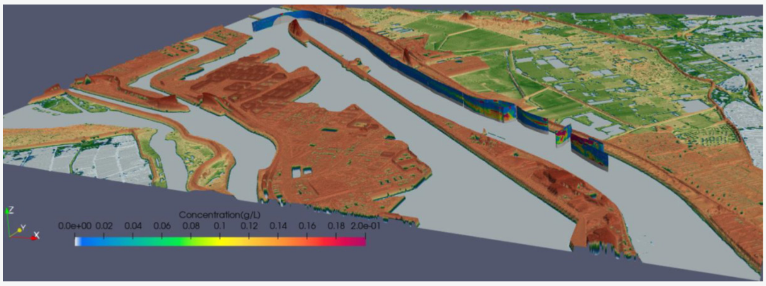


Figure 14 Time lapse of the bathymetry at the barrier, from start (upper left - week 22) to finish (bottom right - week 45), including the closure of the barrier in week 38 (just before and just after the closure).

Mechanism for adapting dredging activity (contd.)	 Figure 15 Up- and downstream change in bathymetry from the reallocation site (midway – bottom part of the red circle). The barrier is in the top left corner of the figure. In addition, the dredging plume was monitored by ADCP backscatter monitoring during a reallocation event (Figure 4).  Figure 16 Dredging plume after reallocation – following the plume from the reallocation site towards the North Sea
Benefit of application of AM	By intensively monitoring the bathymetry in the navigation channel and at the storm surge barrier, the pilot for reallocation of 500,000 m3 showed there was no additional risk for ships or for the safety of the storm surge barrier. This paves the way for the upscaling of the pilot and integrating large scale sediment reallocation within the port as an alternative for sailing towards the North Sea, saving on greenhouse gas emissions.
Further information	https://sednet.org/wp-content/uploads/2021/07/Abstr-CC-8.5.-A.-Wijdeveld.pdf https://sednet.org/wp-content/uploads/2021/07/CC-8.5.-A.-Wijdeveld-changes-in-turbidity-and-bathymetrie-small.pdf https://www.nweurope.eu/projects/project-search/suricates-sediment-uses-as-resources-in-circular-and-territorial-economies/ Arjan.Wijdeveld@Deltares.nl

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11 Annexes

Table 3: Awareness of the concept of AM, overall and per type of stakeholder

Are you familiar with the concept of Adaptive Management (AM) in environmental management of dredging and marine construction works?

Row Labels	No	Yes, I am aware, and I was involved	Yes, I am aware, but have no experience	Grand Total
Contractors	1	1	2	4
Engineering / Consultant	1	7	4	12
Governmental dept / Ministry / Agency	4	3	2	9
Harbour owner / Port Authorities		1	1	2
Employer		2	2	4
Grand Total	6	14	11	31

Table 4: Awareness in the sector of PAM

Are you aware of the application of Pro-Active AM in environmental management of dredging and marine construction works?

Row Labels	No	Yes	Grand Total
Contractors	1	3	4
Engineering / Consultant	5	7	12
Governmental dept / Ministry / Agency	5	4	9
Harbour owner / Port Authorities	1	1	2
Employer	2	2	4
Grand Total	14	17	31

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CEDA Working Group on Adaptive Management

Boudewijn Decrop, IMDC, Belgium

Marc Kindermann, Port of Hamburg, Germany

Alessandra Feola, ISPRA, Italy

Sina Saremi, DHI, Denmark

Marc Huygens, DEME, Belgium

Iolanda Lisi, ISPRA, Italy

Marc Brouwer, HaskoningDHV, the Netherlands

Robrecht Schmitz , Sibelco, Germany

Pierre-Yves Belan, CEREMA, Framce

Volker Steege, Federal Ministry of Transport and Digital Infrastructure, Germany

Wouter Schiettecatte , Jan De Nul, Belgium

Central Dredging Association (CEDA)
Radex Innovation Centre
Rotterdamseweg 183c
2629 HD Delft
The Netherlands
T +31 (0)15 268 2575
E ceda@dredging.org

Central Dredging Association